

Long-Term *RXTE* Monitoring of the Anomalous X-ray Pulsar 1E 1048.1–5937

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Abstract. We report on long-term monitoring of the anomalous X-ray pulsar 1E 1048.1–5937 using the *Rossi X-ray Timing Explorer*. This pulsar’s timing behavior is different from that of other AXPs. In particular, the pulsar shows significant deviations from simple spin-down such that phase-coherent timing has not been possible over time spans longer than a few months. We show that in spite of the rotational irregularities, the pulsar exhibits neither pulse profile changes nor large pulsed flux variations. We discuss the implications of our results for AXP models. We suggest that 1E 1048.1–5937 may be a transition object between the soft gamma-ray repeater and AXP populations, and the AXP most likely to one day undergo an outburst.

INTRODUCTION

The nature of anomalous X-ray pulsars (AXPs) has been a mystery since the discovery of the first example some 20 years ago. Although it is clear that AXPs are young neutron stars, it is not clear why they are observable. In particular, they show no evidence for possessing a binary companion, making conventional accretion problematic. Furthermore, given their spin periods and period derivatives, their rate of loss of rotational kinetic energy is orders of magnitude too small for these sources to be rotation-powered. One important clue is that two AXPs (and one AXP candidate) are clearly associated with supernova remnants. Although only five AXPs are known, their origin is likely to be of great importance to our understanding of the fate of massive stars and the basic properties of the young neutron star population. For an excellent recent review of these objects, see [16].

Currently there are two models to explain AXPs. One model proposes that AXPs are young, isolated, highly magnetized neutron stars or “magnetars” [5,21]. High magnetic fields ($10^{14} - 10^{15}$ G) are inferred from their spin-down under the assumption of magnetic dipole braking, as well as by association with the soft

gamma repeaters (SGRs) which show AXP-like pulsations in quiescence [10,11], and are thought to have high magnetic fields for independent reasons [21]. The second model of AXP emission is that they are powered by accretion from a fallback disk of material remaining from the supernova explosion [4].

One way to distinguish between these classes of models may be through timing observations. In the magnetar model, relatively smooth spin-down should be expected, punctuated by occasional abrupt spin-up or spin-down events or “glitches,” as well as low-level, long-time-scale deviations from simple spin-down, or “timing noise.” Both phenomena are well known among young radio pulsars (e.g. [12]), although their physical origins in magnetars may be different given the much larger inferred magnetic field. However, according to the magnetar model, no extended spin-up should be seen. On the other hand, accretion power is usually associated with much noisier timing behavior, which can be correlated with spectral, luminosity, and pulse morphology changes. In addition, some accreting binary systems undergo extended (\sim years) episodes of spin-up, although these generally seem to alternate with long intervals of spin-down [2].

1E 1048.1–5937 is a 6.4 s AXP in the Carina region [20]. It exhibits no evidence for any binary companion, as no Doppler shifts of the pulse period are seen [17], and no optical counterpart to a limiting magnitude of $m_V \sim 20$ has been detected [14]. The pulsar’s spectrum, like those of other AXPs, is well described with a two component model consisting of a soft black body with a power-law tail [18]. Occasional monitoring observations over more than 20 years show that the pulsar is spinning down, though significant deviations from a simple spin-down model have been noted [18,19,1]. The paucity of data thus far has made it impossible to unambiguously identify the origin of the deviations.

Here we report on our monthly *Rossi X-Ray Timing Explorer* (*RXTE*) monitoring of 1E 1048.1–5937 in which we have attempted long-term phase-coherent timing like that achieved for other AXPs [8]. The results described here are reported in more detail in [9].

OBSERVATIONS AND RESULTS

The observations we report on were made with *RXTE*’s Proportional Counter Array (PCA; [7]). Observations of 3–6 ks in length of 1E 1048.1–5937 were made on a monthly basis during 1996 November – 1997 December and 1999 January – 2000 August. In addition, we used archival observations from 1996; these generally had longer integration times than the other data sets. To minimize use of telescope time, our monitoring data consist of brief (usually 3 ks) snapshots of the pulsar. These snapshots suffice to measure pulse arrival times for a phase-coherent timing analysis to good precision. However, for any one epoch, the measured period has typical uncertainty ~ 3 ms, quite large by normal timing standards. Thus, our snapshot method of measuring pulse arrival times can determine spin parameters with extremely high precision only when phase coherence can be maintained. For

details regarding this timing procedure, see [9]. The snapshot observations are always, however, useful for monitoring the source pulsed flux and pulse morphology (see below).

Timing

We maintained unambiguous phase coherence for 1E 1048.1–5937 in our monthly observations from 1999 January 23 through 1999 November 15. We required a fourth-order polynomial to characterize the 17 pulse arrival times obtained in this span. These results alone clearly imply that the rotational behavior of 1E 1048.1–5937 is quite different from that of AXPs 1E 2259+586 and RXS J170849.0–400910. Those AXPs exhibit much more stable rotation on comparable and even longer time scales, that is, terms of higher order than $\dot{\nu}$ are very small or negligible for those pulsars on time scales of over a year [8]. The span 1999 January through November represents the longest over which we can phase-connect timing data from 1E 1048.1–5937. Investigating archival *RXTE* data going back to 1997 for 1E 1048.1–5937, we find timing results that are similar those obtained in our recent monitoring program, namely we are able to maintain phase coherence only over few-month intervals.

We can compare our pulse ephemerides with measurements of pulse frequency made over the past 20 yr in order to look for long-term trends. Figure 1 shows the spin history of 1E 1048.1–5937 with previously measured spin frequencies plotted as points with their corresponding 1σ error bars. Data were taken from a variety of sources [18,19,1]. Our *RXTE* timing results are plotted as lines representing separate, short, phase-connected segments. The dotted line represents an extrapolation of the ν and $\dot{\nu}$ from the 1999 coherent fit. The lower plot shows the same data set with the linear term subtracted off. This emphasizes deviations from the simple linear trend.

Pulsed Flux and Pulse Morphology

In accreting systems in which the neutron star is undergoing spin-up, changes in torque should be correlated with changes in X-ray flux. AXPs are spinning down, however. Chatterjee et al. (2000) suggest that AXPs might be spinning down in the propeller regime due to accretion from a fall-back disk. In that case, although the physics of the propeller regime is not well understood, it is still likely that L_x should be correlated with torque [9].

Given the large field-of-view of the PCA and that the bright, nearby, but unrelated source η Carinae exhibited large flux changes over the course of our observations, direct flux measurements of 1E 1048.1–5937 could not be made with our *RXTE* data. Instead, we determined the pulsed component of the flux by using off-pulse emission as a background estimator. This renders our analysis insensitive to changes in the fluxes of other sources in the field-of-view.

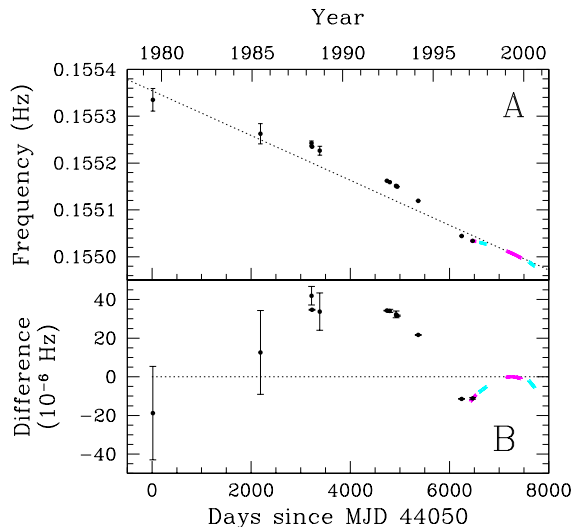


FIGURE 1. Spin history for 1E 1048.1–5937. The points represent past measurements of the frequency of the pulsar. The solid lines represent the *RXTE* phase-connected intervals. See [9] for details. Panel A shows the observed frequencies over time. The dotted line is the extrapolation of the ν and $\dot{\nu}$ of the 1999 phase-coherent ephemeris. Panel B shows the difference between the ephemeris indicated by the dotted line and the data points.

The results are shown in Figure 2. We find no large pulsed flux variations. The χ^2 strictly speaking does suggest some low-level variability; longer individual observations are clearly necessary to verify this is the case. However, as we discuss below, the pulsed flux is certainly much more stable than previous analyses have suggested [18].

We have also used the *RXTE* data to search for pulse profile changes, as many accretion-powered pulsars exhibit significant changes in their average pulse profiles. Such changes can be correlated with the accretion state, and hence accretion torque and timing behavior [2]. Furthermore, X-ray pulse profiles from the SGRs 1806–20 and 1900+14 have shown differences at different epochs depending on time since outburst [10,11]. However, we find no significant changes in the pulse profile morphology in any of the *RXTE* observations of 1E 1048.1–5937.

DISCUSSION AND CONCLUSIONS

Long-term *RXTE* monitoring of the AXP 1E 1048.1–5937 has shown it to be a much less stable rotator than other AXPs, yet its pulse profile and pulsed flux are stable. Previously, Oosterbroek et al. (1998) compiled flux data from a variety of different X-ray instruments that observed 1E 1048.1–5937. That compilation suggested that the pulsar shows variability by over a factor of ~ 5 on time scales of a few years. The reality of those flux changes is not supported by our results. One

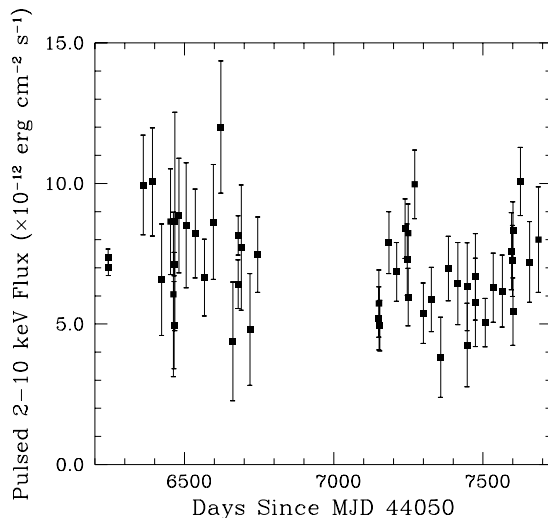


FIGURE 2. Pulsed flux time series in the 2–10 keV band for *RXTE* observations of 1E 1048.1–5937.

caveat is that we measure pulsed flux, while they report flux, so the results could be reconciled if the pulsed fraction is variable.

In the context of the magnetar model, we note that the timing behavior of 1E 1048.1–5937 is somewhat similar to that observed for the soft gamma repeaters SGR 1806–20 and 1900+14 [13,23,24]. However, as the stable flux time series (Fig. 2) for the AXP shows, it has not undergone any outbursts. This can perhaps be understood in terms of persistent seismic activity and small-scale crustal fractures [22] or low amplitude toroidal modes resulting in angular momentum loss following crustal twisting fractures [6].

1E 1048.1–5937 is unusual among AXPs for reasons other than just its timing behavior. In particular, it shows the highest ratio of blackbody to total flux (once energy band is accounted for), and the largest pulsed fraction. In addition, it has the lowest photon index for the power-law tail in its spectrum of any AXP, which makes it the closest to those measured in the X-ray band for SGRs 1806–20 and 1900+14. Further, the thermal component of 1E 1048.1–5937’s spectrum has the highest temperature (0.64 keV) of any AXP. This temperature is comparable to that seen for SGR 1900+14 post-burst, 0.62 keV [24]. It therefore could be the case that 1E 1048.1–5937 is a transition object between the populations of AXPs and SGRs, and the AXP most likely to one day undergo an outburst.

In the context of accretion models, perhaps the best source with which to compare 1E 1048.1–5937 is 4U 1626–67, a 7.7 s accreting pulsar in a 42-min binary with a low-mass companion. Although 1E 1048.1–5937 is noisy by AXP timing standards, its noise is comparable in strength to that of 4U 1626–67 [3]. Still, we regard the case for 1E 1048.1–5937 as an accreting binary, even with a very low-mass

companion, as weak, given the other evidence against this hypothesis, namely, its much softer spectrum than other accreting binaries, the absence of pulsed flux or pulse morphology changes correlated with the timing behavior, and the spin-down over some 20 yr. It is more difficult to dismiss the possibility that 1E 1048.1–5937 is accreting from a supernova fall-back disk, since there is not yet a consensus on the properties such a disk would have or on the expected timing and variability properties of the pulsar. However, one expectation is that such a disk would be a significant emitter in the optical and infrared, Future optical/IR observations following a more precise localization using the *Chandra X-ray Observatory* could test the fallback disk model.

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